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A new approach to assessing the water footprint of hydroelectric power based on allocation of water footprints among reservoir ecosystem services

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ABSTRACT

Hydroelectric power is an important energy source to meet the growing demand for energy, and large amounts of water are consumed to generate this energy. Previous studies often assumed that the water footprint of hydroelectric power equaled the reservoir's water footprint, but failed to allocate the reservoir water footprint among the many beneficiaries; dealing with this allocation remains a challenge. In this study, we developed a new approach to quantify the water footprint of hydroelectric power (WF_h) by separating it from the reservoir water footprint (WF) using an allocation coefficient (η_h) based on the ratio of the benefits from hydroelectric power to the total ecosystem service benefits. We used this approach in a case study of the Three Gorges Reservoir, the world's largest reservoir, which provides multiple ecosystem services. We found large differences between the WF_h and the water footprint of per unit of hydroelectric production (PWF_h) calculated using η_h and those calculated without this factor. From 2003 to 2012, η_h decreased sharply (from 0.76 in 2005 to 0.41 in 2012), which was due to the fact that large increases in the value of non-energy ecosystem services, and particularly flood control. In 2009, flood control replaced hydroelectricity as the largest ecosystem service of water from the Three Gorges Reservoir. Using our approach, WF_h and PWF_h averaged 331.0×10^6 m^3 and 1.5 m^3 GJ^{-1}, respectively. However, these values would almost double without allocating water footprints among different reservoir ecosystem services. Thus, previous studies have overestimated the WF_h and PWF_h of reservoirs, especially for reservoirs that serve multiple purposes. Thus, the allocation coefficient should not be ignored when calculating the WF of a product or service.

1. Introduction

Water and energy are critical natural resources that sustain modern civilization. As one of the planet's most valuable resources, freshwater is an essential life-sustaining element that cannot be replaced (Koehler, 2008). During socioeconomic development, humans consume increasing amounts of water and energy. As a result, it is a growing challenge to meet humanity's water and energy security needs. Currently, 1.1 billion people lack adequate access to water (UNEP, 2006) and 1.5 billion lack access to electricity (IEA, 2009). About one-third of the world's population suffers from a water scarcity, and this may increase to two-thirds by the end of the 21st century in the worst-case scenario (Vörösmarty et al., 2010; Oki and Kanae, 2006). Global energy demand is projected to grow by 40% between now and 2030. Almost all of the growth will come from countries that do not belong to the Organization for Economic Co-operation and Development, and China, India, and the Middle East are expected to double their primary energy demand (IEA, 2009). Electricity is the fastest growing form of energy, and is projected to grow by 87% by 2035 (UNEP, 2011a), with almost one-third of that growth coming from China alone (IEA, 2009). According to China's Energy Policy 2012 (Information Office of the State Council, 2012), China's goal is to increase consumption of non-fossil energy to 15% of the total energy consumption by 2020, with more than half of this total coming from hydroelectric power (The National Development and Reform Committee, 2008).

As one of the most popular forms of renewable energy, hydroelectricity is often regarded as a clean and environmentally friendly energy source. However, reservoirs create many problems; in the context of the present paper, the most significant problem is that hydroelectricity generation consumes water resources. Storage of water behind hydroelectric power dams leads to a large

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amount of consumptive water use through evaporation from the open water surface. Hydropower provides about 21% of global electricity consumption and 86% of the global renewable energy consumption (IEA, 2010). Water consumption caused by hydroelectricity generation may exacerbate regional water scarcity problems (Fthenakis and Kim, 2010; Gerbens-Leenes et al., 2009; Gleick, 1993). Hence, it is urgently necessary to accurately assess the water consumption of hydroelectric power.

The water footprint (*WF*) concept was proposed by Hoekstra (2003). The *WF* of a product can be defined as the amount of water used to produce the product, including all consumption throughout the supply chain (Hoekstra et al., 2011). By identifying the impacts of human production and consumption behavior on water consumption and pollution generation, *WF* can be used to measure the effect of humans on the available water resource and on the environment. *WF* provides a rational and holistic perspective on the relationship between consumers and producers and the water system that sustains them (Hoekstra et al., 2011).

In recent years, three approaches have been applied to assess the water consumption of a reservoir: in the gross water consumption method (Gleick, 1992; Mekonnen and Hoekstra, 2012), the gross water evaporation from different water sources is accounted for except for treated wastewater. In the net water consumption method, the above gross evaporation is subtracted by the land surface evaporation that was used before the reservoir was built (Herath et al., 2011). In the water balance method, the reservoir is regarded as closed watershed, and both outputs (e.g., evaporation, river flow) and inputs (e.g., rainfall, release of treated wastewater) are accounted for. The difference between annual water outputs and inputs is used to represent the total amount of water consumed by a reservoir (Herath et al., 2011; Yesuf, 2012; Arnøy, 2012). Gross water consumption has been used in most studies (Gerbens-Leenes et al., 2009; Mekonnen and Hoekstra, 2012; Pasqualetti and Kelley, 2008; Torcellini et al., 2003), and it is the dominant method for estimating water consumption by hydroelectric power plants. The *WF* of hydroelectric power plants in different regions ranges from only 0.01 $m^3\,GJ^{-1}$ (Gleick, 1992) to 846 $m^3\,GJ^{-1}$ (Mekonnen and Hoekstra, 2012). However, research on the *WF* of hydroelectric power remains in its infancy (Arnøy, 2012; Demeke et al., 2013; Gerbens-Leenes et al., 2009; Gleick, 1994, 1993, 1992; Herath et al., 2011; Mekonnen and Hoekstra, 2012; Pasqualetti and Kelley, 2008; Tefferi, 2012; Torcellini et al., 2003; Yesuf, 2012).

The *WF* of a reservoir in previous studies was assumed to equal the *WF* of hydroelectric power. This is problematic because it allocates all water consumption by a multi-purpose reservoir to hydroelectric power, even if the reservoir provides many other services. As a result, this approach overestimates the *WF* of hydroelectric power (Herath et al., 2011; Mekonnen and Hoekstra, 2012). In the present study, we used a new approach to quantify the water footprint of hydroelectric power (WF_h) by developing an allocation coefficient (η) that estimates the ratio of the ecosystem services value of hydroelectricity to the total ecosystem services value of a reservoir. We applied this approach to the Three Gorges Reservoir, the world's biggest reservoir, to demonstrate the insights provided by the new method.

2. Methods and data sources

Hoekstra et al. (2011) defined *WF* with three components: the green water *WF* (i.e., consumptive use of soil water), the blue water *WF* (i.e., consumptive use of ground or surface water), and the grey water *WF* (i.e., the volume of polluted water). Reservoirs consume mainly surface water (blue water) through the process of evaporation, but consume little or no soil water (green water) and produce little or no grey water (Mekonnen and Hoekstra, 2012). Thus, our analysis focuses on blue water consumption arising from evaporation from the artificial reservoirs that develop behind hydroelectric dams.

2.1. A new approach to assess the water footprint of hydroelectric power based on an allocation coefficient

In previous studies, the *WF* of reservoirs was used to represent the WF_h. However, this is only suitable for reservoirs whose only or primary purpose is to generate hydroelectricity, and is inappropriate for reservoirs that provide multiple ecosystem services (e.g., flood control, irrigation). Approximately 25% of the world's reservoirs with a dam higher than 15 m are multi-purpose reservoirs (ICOLD, 2013). Some reservoirs provide many ecosystem services, including hydroelectricity, flood control, navigation, water supply, and fisheries (Ministery of Water Resources, 2012). The traditional gross water consumption method will therefore overestimate WF_h because it does not allocate the overall *WF* among all services. Hence, for reservoirs that provide multiple ecosystem services, it is necessary to allocate the total *WF* among the ecosystem services. We used the following approach to accomplish this:

$$WF_r = \sum_{i=1}^{n} WF_i = \sum_{i=1}^{n} (\eta_i \times WF_r) \tag{1}$$

where WF_r is the total water footprint of the reservoir, WF_i is the water footprint of ecosystem service *i*, and η_i is the allocation coefficient for ecosystem service *i*, and $\eta_1 + \eta_2 + \ldots \eta_n = 1$.

In this new approach, it is necessary to accurately determine the allocation coefficients, since this will determine the accuracy of the estimated footprint of each service. We defined the allocation coefficient (η_h) as the ratio of the benefit obtained from hydroelectricity to the total benefits provided by a reservoir. The detailed procedure is as follows:

1. Assess the total economic value of all ecosystem services provided by the reservoir.
2. Calculate the ratio of the economic value of hydroelectricity to the total economic value of all ecosystem services. This ratio is the allocation coefficient (η_h).
3. Calculate WF_h by multiplying the gross water footprint of the reservoir (WF_r) by the allocation coefficient (η_h).

WF_r ($m^3\,yr^{-1}$) equals the annual total amount of water that evaporates from the reservoir, which is estimated by multiplying the annual water evaporation by the surface area of the reservoir:

$$WF_r = 10 \times E \times A \tag{2}$$

where *E* is the annual evaporation ($mm\,yr^{-1}$), *A* is the surface area of reservoir (ha), and 10 is a constant used to convert mm into $m^3\,ha^{-1}$.

The water footprint of hydroelectric power is calculated as follows:

$$\eta_h = R_h / R \tag{3}$$

$$WF_h = WF_r \times \eta_h \tag{4}$$

where R_h is the economic value of hydroelectricity ($\times 10^9$ CNY), *R* is the total economic value of all ecosystem services ($\times 10^9$ CNY), and WF_h is the *WF* of hydroelectric power.

The product water footprint of hydroelectric power (PWF_h, $m^3\,GJ^{-1}$), which represents the water footprint per unit of production, is calculated by dividing WF_h by the amount of energy generated (*EG*, $GJ\,yr^{-1}$).

$$PWF_h = \frac{WF_h}{EG} \tag{5}$$

In this article, we used an ecosystem service approach to evaluate the main economic values provided by a reservoir (Badola and Hussain, 2005; Bateman et al., 2003; Constanza et al., 1997; Godoy et al., 1993; Kim and Dixon, 1984). Based on an economic assessment of the Three Gorges Water Conservancy Key Project (Yangtze River Water Resources Commission, 1992), we identified six key ecosystem services provided by the Three Gorges Reservoir: flood control, hydroelectricity, navigation, water supply, aquaculture, and recreation (Table 1). We divided these services into two categories: use values (including flood control, hydroelectricity, navigation, water supply and aquaculture) and non-use values (recreation). Different ecosystem services require different quantitative approaches. We estimated the use values using a market valuation method (Bateman et al., 2003) or a damage cost avoided method (Badola and Hussain, 2005). For the non-use value, we used the travel cost method (Randall, 1994).

Based on the results of a previous study (Sun et al., 2012), we determined the water surface area of the Three Gorges Reservoir annually (Table 3). We obtained evaporation values from 2003 to 2012 based on data from seven hydrological stations (Fig. 1) in the Three Gorges Reservoir region (Government of China, 2004–2013). We used the Thiessen polygon method (Thiessen, 1911) to allocate evaporation to the reservoir water surface (Fig. 1).

2.2. Study area

The Three Gorges Water Project, the largest reservoir project in the world, is located between 106°00′E and 111°00′E, and between 29°16′N and 31°25′N, in the upper reaches of the Yangtze River. It has a catchment formed from three large gorges, and its normal water level is currently maintained at 175 m above sea level located at Wusongkou of Shanghai, creating an average water surface area of 1080 km^2. The climate is a subtropical humid monsoon. The annual average temperature ranges from 17 to 19 °C, with a maximum of 42.6 °C and a minimum of -4 °C. The annual precipitation ranges between 1120 and 1200 mm.

Table 1
Methods used to calculate the ecosystem services values and the resulting allocation coefficients (η).

Ecosystem service	Calculation method	Description of method	Data sources and description
Hydroelectricity	Market valuation (Bateman et al., 2003; Cairns, 2002)	Multiplying power generation ($\times 10^9$ kWh) by the price of electricity (CNY kWh^{-1}) provided the hydroelectricity value ($\times 10^9$ CNY)	Power generation was obtained from (China Three Gorges Corporation, 2014), and the electricity price was 0.25 CNY kWh^{-1} from 2003 to 2010 (National Development and Reform Commission, 2003), then increased to 0.2519 CNY kWh^{-1} in 2011 and 2012 (National Development and Reform Commission, 2011)
Water supply	Market valuation	Multiplying water volume by the price of water represented the direct economic value ($\times 10^9$ CNY)	The Three Gorges Reservoir supplied water to channels and arable land in the middle and downstream reaches of the Yangtze River (including Xiangxi River, Daning River, Xiangjiang River etc.). Water price was got from China Water Network (2001), and water volume was from China Three Gorges Corporation (2007–2012, 2014)
Aquaculture	Market valuation	Multiplying the aquaculture area (ha) by the unit production (kg ha^{-1}) and price (CNY kg^{-1}) of each product	The areas were obtained from Yangtze River Water Resources Commission (1992), and the production and prices were obtained from Ministry of Agriculture Fisheries Bureau (2004–2013)
Navigation	Market valuation	This value was equal to the gross of commodity transport benefit and passenger transport benefit	The Three Gorges Reservoir allowed the transport of commodities and passengers. The China Three Gorges Corporation (2014) recorded the amount of commodities ($\times 10^6$ t-km yr^{-1}) and passengers ($\times 10^6$ per-km yr^{-1}) from 2003 to 2012. We obtained the prices of commodities and the number of passengers from Xiao et al. (2007)
Flood control	Damage cost avoided (Badola and Hussain, 2005)	Multiplying storm storage volume by the unit flood control benefit	In 2010, the Yangtze River Water Resources Commission estimated the flood control benefits provided by the Three Gorges Reservoir using the damage cost avoided method. The result was about 1 CNY m^{-3} (Zhi and Zhong, 2010). The storm storage volume was obtained from (China Three Gorges Corporation, 2014)
Recreation	Travel cost (Heal, 2000)	The product of travel cost and the number of travelers represented the total recreation value	The China National Tourism Administration (2004–2013) investigated the travel cost per year (CNY $person^{-1}$ yr^{-1}). We collected data (China Network, 2007; China Three Gorges Corporation, 2007–2008; Xinhua Network, 2010; China Universal Travelling Network, 2011) on the number of travelers each year in the Three Gorges Reservoir

Note: "CNY" represents Chinese yuan. As of late May 2014, the exchange rate was 6.24 CNY per 1 USD.
Economic values represent current prices, GDP Index was used to transform constant price into current price.
Table 2 presents the actual ecosystem service values for the Three Gorges Reservoir that we used in our analysis.

Table 2
Ecosystem service values in the Three Gorges reservoir.

	Ecosystem service value ($\times 10^9$ CNY)						
Year	Hydroelectricity	Water supply	Aquaculture	Navigation	Flood control	Recreation	Total
2003	2.15	0.03	0.85	0.72	–	0.23	3.98
2004	9.79	–	1.14	2.03	0.39	0.31	13.65
2005	12.27	–	1.25	2.20	–	0.46	16.18
2006	12.31	–	1.27	2.62	–	0.53	16.73
2007	15.40	0.18	1.42	3.17	0.95	0.60	21.72
2008	20.20	0.12	1.69	3.59	1.31	0.47	27.39
2009	19.96	0.35	1.67	3.72	5.34	0.62	31.66
2010	21.09	0.64	1.52	4.58	26.63	0.81	55.27
2011	19.72	1.20	1.62	6.06	20.01	1.28	49.89
2012	24.71	1.19	1.86	5.20	25.69	1.38	60.03

Table 3
Reservoir water footprint (WF_r), hydroelectric power water footprint (WF_h) and product water footprint (PWF_h) in the Three Gorges Reservoir from 2003 to 2012.

Year	Evaporation (mm yr^{-1})	Water surface area (Sun et al., 2012) (km^2)	Reservoir WF_r ($\times 10^6$ m^3)	η	Hydroelectric power WF_h (with η) ($\times 10^6$ m^3)	Hydroelectric generation ($\times 10^8$ kWh)	PWF_h (without η) (m^3 GJ^{-1})	PWF_h (with η) (m^3 GJ^{-1})
2003	647.7	816.3	528.7	0.54	285.8	86.1	17.1	9.2
2004	715.2	842.1	602.3	0.72	431.9	391.6	4.3	3.1
2005	663.8	842.9	559.5	0.76	424.5	490.9	3.2	2.4
2006	692.5	879.4	608.9	0.74	448.2	492.5	3.4	2.5
2007	704.4	967.9	681.8	0.71	483.4	616.0	3.1	2.2
2008	713.8	1000.3	714.0	0.74	526.7	808.1	2.5	1.8
2009	676.9	1058.1	716.3	0.63	451.7	798.5	2.5	1.6
2010	662.8	1072.5	710.8	0.38	271.3	843.7	2.3	0.9
2011	772.5	1084.2	837.6	0.40	331.1	782.9	3.0	1.2
2012	600.5	1084.0	650.9	0.41	268.0	981.1	1.8	0.8
Average	685.0	964.8	661.1	0.50	331.0	629.1	2.9	1.5

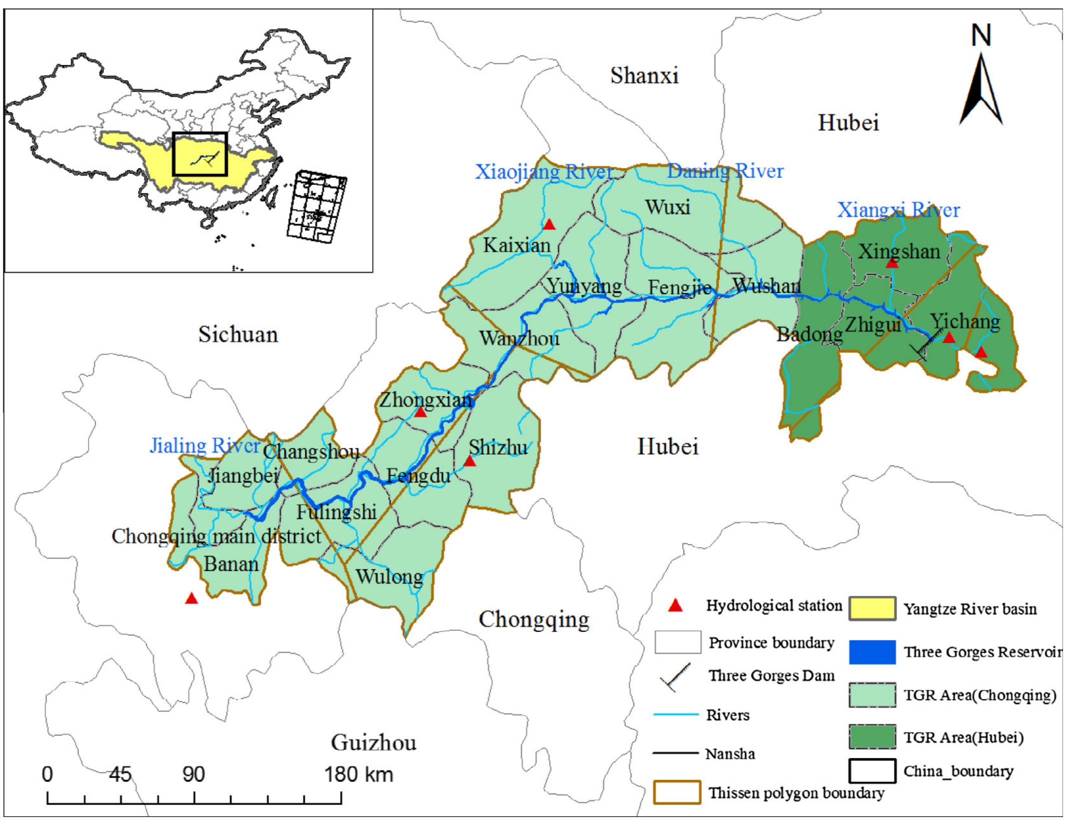

Fig. 1. Location of the Three Gorges Reservoir in China.

The reservoir's total water storage capacity is 39.3×10^9 m^3, and more than half of this storage capacity is used to control flooding. The region's climate varies widely both within and between years, so the length of the reservoir water surface ranges from 600 to 670 km, with an average width of 1100 m and an average depth of 70 m at a surface elevation of 175 m. The reservoir's hydroelectric power plant is the biggest in the world, with an installed capacity of 22,500 MW, however, because of other demands for water; it can only generate 84.7×10^9 kWh. The dam is located at around 110°59′46″E and 30°49′44″N, and is 185 m tall.

The Three Gorges Water Project began to construct in 1994, and when the reservoir water level reached 135 m in 2003, the hydroelectric power plant begins generating electricity and navigation began across the reservoir. In 2006, the water level reached 156 m, and the flood control and water supply services began. The water level reached 175 m in 2009, when construction was complete. Since then, it has provided the entire ecosystem functions described in Section 2.1.

3. Results

3.1. Water footprint of the Three Gorges Reservoir

Table 3 presents the reservoir and hydroelectric power *WF* and the corresponding *PWF* values from 2003 to 2012. Based on the traditional gross water footprint method, the reservoir *WF* ranged from 528.7×10^6 m^3 (2003) to 837.6×10^6 m^3 (2011). The minimum *WF* is only 63% of the maximum, and *WF* averaged 661.1×10^6 m^3. On this basis, the maximum *PWF* was 17.1 m^3 GJ^{-1} (in 2003), and the minimum was 1.8 m^3 GJ^{-1} (in

2012). The maximum was therefore nearly 10 times the minimum, so *PWF* varied widely from year to year. The Three Gorges Water Project was still under construction for much of the period from 2003 to 2012, so it is not surprising that the reservoir area, *WF*, and hydroelectric power generation generally increased during this period. Without allocating WF_r among the different ecosystem services, WF_h averaged 2.9 $m^3\,GJ^{-1}$ from 2003 to 2012, with the highest value (17.1 $m^3\,GJ^{-1}$) occurring in 2003. WF_h generally decreased from 2003 to 2012, despite growing electricity consumption, because flood control replaced electricity generation as the dominant ecosystem service.

3.2. Allocation coefficients (η)

The Three Gorges Reservoir is a multi-purpose reservoir that provides the main ecosystem services of flood control, hydroelectricity, navigation, water supply, aquaculture, and recreation (Liu et al., 2013). According to the method provided in Section 2.1 and Table 1, we evaluates the ecosystem service value of Three Gorges Reservoir, as it is shown in Table 2. Fig. 2 shows that before 2009, hydroelectricity was the main service provided by the reservoir, with $\eta_h > 0.6$. The next-largest ecosystem service values during this period were from navigation and aquaculture. The reservoir provided little flood control before 2009, but thereafter, the flood control service increased greatly, accounting for nearly half of the total benefit. As a result, η_h decreased gradually to 0.41 in 2012. Since 2009, flood control and hydroelectricity have achieved roughly equal importance, but navigation has also been important.

3.3. Water footprint of hydroelectric power

WF_h averaged $331.0 \times 10^6\,m^3$, with a maximum of $526.7 \times 10^6\,m^3$ (in 2008) and a minimum of $268.0 \times 10^6\,m^3$ (in 2012) (Table 2). These values are about half the corresponding WF_r values. In addition, the smallest WF_h calculated without the allocation coefficient was larger than the largest WF_h calculated using the allocation coefficient. We calculated an average of PWF_h of 1.5 $m^3\,GJ^{-1}$, which is only about half of that calculated without considering the allocation coefficient. The smallest PWF_h was 0.8 $m^3\,GJ^{-1}$ (in 2012) and the largest was 9.2 $m^3\,GJ^{-1}$ (in 2003). The traditional method clearly overestimates both WF_h and PWF_h.

4. Discussion

Mekonnen and Hoekstra (2012) reported that nearly 90% of the 35 reservoirs they studied had a *PWF* (calculated using the traditional method, without an allocation coefficient) that ranged from 0.3 $m^3\,GJ^{-1}$ to 846 $m^3\,GJ^{-1}$. The average PWF_h value of 1.5 $m^3\,GJ^{-1}$ for the Three Gorges Reservoir was lower than 32 of those reservoirs. However, a strict comparison is not possible because Mekonnen and Hoekstra assumed that WF_h equaled WF_r. In reality, most of these reservoirs provide a range of ecosystem services, and electricity is only one of the services; thus, their results were likely to overestimate the true footprints of hydroelectric power.

Gleick (1994) and Gerbens-Leenes et al. (2009) estimated *PWF* of wind, nuclear, natural gas, coal, solar thermal, crude oil and biomass. We compared the *PWF* of hydroelectric based on the η_h with the *PWF* of other primary energy types in order to understand which approach is more water efficient to produce energy. As shown in Fig. 3, there are large differences among the different energy types from below 0.1 $m^3\,GJ^{-1}$ for wind energy to over 70 $m^3\,GJ^{-1}$ for biomass. The comparison indicates that hydropower has no advantages over water consumption per unit of energy production when compared to other energy sources (biomass excluded).

In this study, we focused on how to calculate WF_h for a reservoir that provides multiple services. In the traditional method, WF_r equals WF_h (Arnøy, 2012; Demeke et al., 2013; Gerbens-Leenes et al., 2009; Gleick, 1994, 1993, 1992; Herath et al., 2011; Mekonnen and Hoekstra, 2012; Pasqualetti and Kelley, 2008; Tefferi, 2012; Torcellini et al., 2003; Yesuf, 2012). The new method is more realistic because it assesses the contribution of hydroelectricity to the total reservoir footprint.

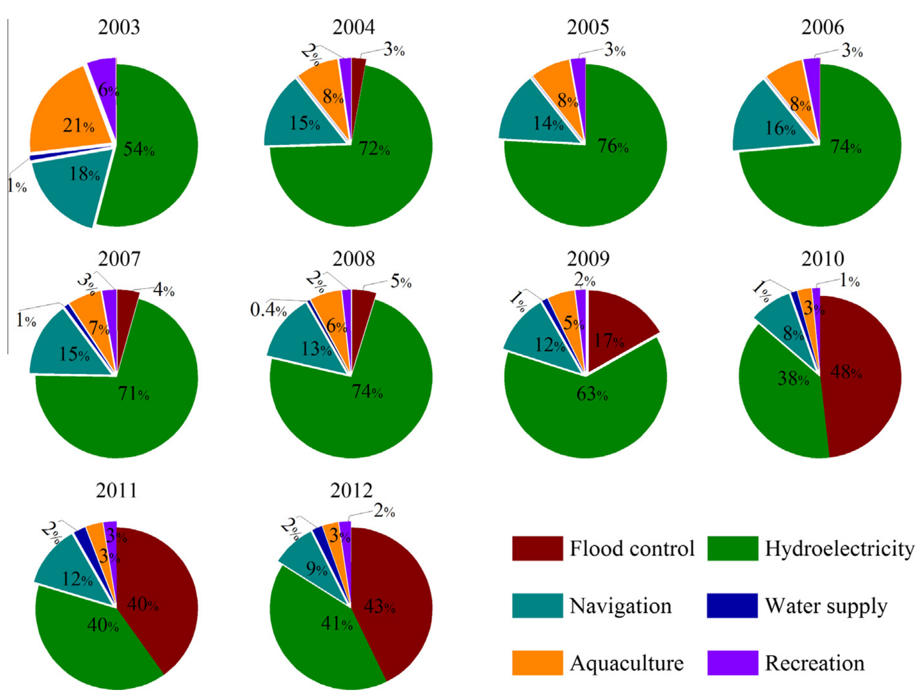

Fig. 2. Allocation coefficients (η) for the six ecosystem services.

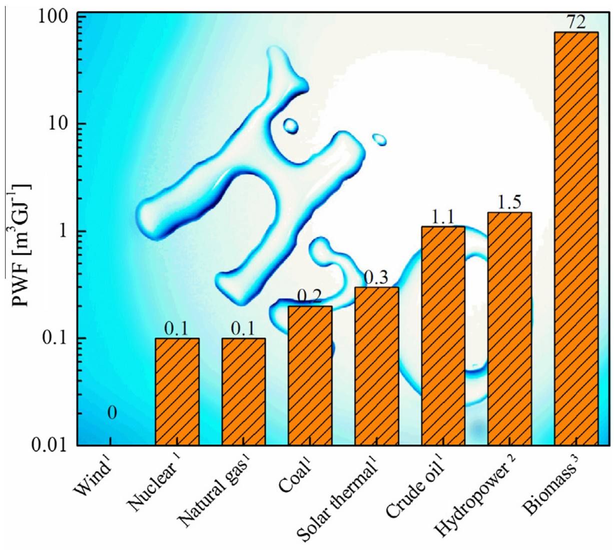

Fig. 3. PWF of primary energy types [1]Data source: Gleick (1994) [2]Data source: This study. [3]Data source:Gerbens-Leenes et al. (2009).

The Three Gorges Reservoir, as the largest reservoir in the world, has attracted worldwide attention for its impacts on the environments. This study presents a better method to quantify the amount of water use to produce hydropower. This information is of importance to assess the environmental impacts (in particular, the aquatic impacts) of hydropower supplied by reservoirs.

Nevertheless, our allocation coefficient approach has certain limitations. First, a reservoir generally also provides indirect ecosystem services such as reducing CO_2 and SO_2 emissions and protecting biodiversity. Many of these services cannot be easily quantified, and the accuracy of using our approach will depend on the availability of data on these indirect services and the selection of appropriate indicators to quantify their values. Second, ecosystem service values may not be exactly proportional to the volume of water that is consumed by these services. This is because water will not be used with 100% efficiency and because the prices used to calculate the values may not reflect the true cost of the water. Third, a reservoir's water surface fluctuates dynamically over time, leading to different evaporation rates. The difference between the minimum and maximum areas over a multi-year period also shows high variation between years. Reported areas generally refer to the maximum area within a year, and relying on the maximum instead of a more precise estimate, such as a weighted mean value, can lead to overestimation of evaporation during the year. Fourth, we did not assess the supply-chain *WF* of hydroelectric generation. This footprint accounts for the *WF* of producing the materials used in the construction, operation, and maintenance of the hydroelectric plant, and although we expect this value to be much smaller than the operational *WF*, it may not be so small that it should be ignored (Inhaber, 2004; Fthenakis and Kim, 2010). Fifth, we calculated WF_r by accounting for the total evaporation from the reservoir. This ignores the fact that there was some evaporation from the reservoir area before the reservoir was created, and that it may be appropriate to subtract this amount from WF_r to better reflect the magnitude of the human impact. However, the total evaporation from the original bodies of water is likely to be considerably smaller than that from the reservoir because the reservoir covers a much larger area than the original bodies of water (Mekonnen and Hoekstra, 2012). We believe that it is not necessary to account for the change that has occurred since the reservoir was constructed, since *WF* is meant to quantify the volume of consumptive water use associated with a specific human purpose (here, electricity generation) rather than the change in consumption after reservoir construction (Mekonnen and Hoekstra, 2012). From this perspective, the full value of reservoir evaporation should be used to calculate *WF*.

Although we quantified the reservoir's evaporative water losses, it is worth noting that for such a large reservoir, some of the evaporated water will return to the reservoir or its catchment as precipitation. We assumed that little or none of this evaporated water will return to the reservoir or the catchment, but this assumption should be confirmed in future research. A final problem is that such a drastic land-use change can influence climate at a regional or continental scale through its impact on the water cycle (Eltahir and Bras, 1996; van der Ent et al., 2010). However, this process operates in larger scale than the catchment scale. This is another reason to predict that most of the water that evaporated from a reservoir can be treated as "lost" and unavailable for use in the same catchment.

5. Conclusion

In this paper, we developed a new "allocation coefficient" approach to estimate the *WF* of hydropower by separating it from *WF* of reservoir. This coefficient was calculated with the ratio of economic value of hydroelectricity to the total economic value of all ecosystem services of the reservoir. We used this approach for a case study of the Three Gorges Reservoir, the largest reservoir in the world. The results indicated that previous approach often overestimated the WF_h and PWF_h of hydropower, especially for the reservoirs with multiple ecosystem services. Our study showed that allocation coefficient should not be ignored when calculating *WF* of hydropower of reservoirs.

Conflict of interest

The authors have no conflict of interest.

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